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The effects of pollutants on global climate*

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Summary

Man has the potential to change the earth's climate by altering the composition of the atmosphere. This paper discusses the physical processes through which certain gases influence climate, summarizes those constituents which are most likely to make a significant contribution to the climate change over the next few decades, and illustrates how numerical models are being used to estimate details of such changes in climate.

1. Introduction

Over the last decade there has been a growing interest in man's impact on climate (Massachusetts Institute of Technology 1971; National Academy of Sciences 1979a, 1982; Bach *et al.* 1979). This increase in awareness has been fostered, at least in part, by the improved monitoring of trace gases in the atmosphere (for example, Keeling *et al.* 1982) and by our increased understanding of the influence of these gases on climate through the use of numerical models of climate (for example, Mason 1976). The first climate impact research program to make extensive use of mathematical models of climate was stimulated by the possibility that supersonic aircraft could alter the concentration of stratospheric ozone. The US Government set up their climate assessment program (Grobecker *et al.* 1974), and were quickly followed by the French (COVOS 1976) and the United Kingdom (Meteorological Office 1975). More recent studies have been concerned with the effects of chlorofluorocarbons on the stratosphere (National Academy of Sciences 1976, 1979b) and carbon dioxide (CO_2) on the troposphere (see for example, Clark 1982). In 1978 the World Meteorological Organization set up its World Climate Research Programme to co-ordinate research at an international level.

Recently there has been much concern that a global warming due to increases in CO_2 and other radiatively active gases could produce changes in global patterns of temperature, precipitation and winds. This has led to speculation that agriculture may be adversely affected and, in particular, that the

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main regions of grain production will become more arid. There have also been suggestions that the predicted rises in polar temperatures are sufficient to cause rapid disintegration of the vast grounded west Antarctic ice sheet. This would raise sea level by about 5 metres and flood many of the world's major cities. While some of these conjectures are probably exaggerated, there is much evidence that changes following an increase in CO_2 and other trace gases will be significant.

This paper is concerned with the effects of pollutants on global climate. Most of the paper is devoted to modelling the effects of increased CO_2. Other trace gases are discussed, and many aspects of CO_2 research are relevant to other radiatively active gases. The next section contains a brief description of the physical processes by which pollutants may alter climate. In the third section, I discuss the atmospheric constituents which are thought likely to affect climate, and give a crude estimate of their potential to change global mean surface temperature. In the following section, the validity of the simple climate models used to obtain these estimates of temperature change is assessed. Results from three-dimensional models of climate are presented in the penultimate section. This is followed by some concluding remarks and a short summary.

2. The physical processes by which pollutants affect climate

The earth–atmosphere system is heated by short-wave radiation (wavelengths up to about 4×10^{-6} m) from the sun and cooled by long-wave radiation to space. The intensity of radiation emitted from a body increases with temperature. The temperature of the earth and atmosphere is such that, in the long term, the outgoing long-wave radiation at the top of the atmosphere just balances the net incoming radiation from the sun. In the absence of the atmosphere, the earth's surface temperature would be about 255 K, some 30 K lower than at present (assuming the earth continued to reflect about 30% of the incident solar radiation). The presence of the atmosphere raises the surface temperature owing to a combination of two effects. First, clouds and certain atmospheric gases (for example, water vapour, carbon dioxide and ozone, but not oxygen or nitrogen) absorb and emit long-wave radiation. Thus, much of the terrestrial radiation reaching space originates from the atmosphere rather than the earth's surface. Second, the temperature of the lower atmosphere (troposphere) decreases with height at a mean rate of 6 K km^{-1}. Hence, radiation from the atmosphere is emitted at a lower temperature than that of the surface. An observer in space would receive long-wave energy consistent with an emitting temperature of 255 K, corresponding to a level about 5 km above the ground, but the surface is some 30 K warmer. This anomalous increase in surface temperature is often referred to as the greenhouse effect. Water vapour is responsible for the largest contribution to this warming.

If the concentration of an atmospheric constituent which absorbs long-wave radiation is increased, this 'greenhouse' effect will be enhanced. The magnitude depends not only on the size of the increase, but also on the extent to which the constituent absorbs radiation, which is a function of its molecular structure, and whether or not other atmospheric gases are already absorbing radiation at the same wavelength. Water vapour and carbon dioxide already absorb long-wave radiation at most wavelengths from 4 to 8×10^{-6} m and above 13×10^{-6} m. At the intermediate wavelengths, sometimes known as the atmospheric window, the atmosphere absorbs little radiation in the absence of cloud, and energy escapes directly from the surface to space. Gases which absorb over this spectral interval will be more effective in contributing to the greenhouse effect.

Many atmospheric pollutants have the potential to alter global climate by enhancing the earth's greenhouse effect, as is discussed in the following section. Some pollutants may also affect climate indirectly through chemical reactions which alter the concentration of radiatively active gases. Most of these reactions are associated with the presence of ozone in the upper atmosphere. Ozone is formed following the absorption of solar radiation by molecular oxygen in the middle stratosphere and is removed in the lower stratosphere by photodissociation, which produces excited oxygen atoms, and by

further reactions with these excited oxygen atoms. Ozone is also destroyed in catalytic chain reactions involving certain chemical fragments (free radicals) including OH, H, NO and Cl. These radicals can be injected directly into the atmosphere (for example, NO from oxides of nitrogen produced in the exhausts of stratospheric aircraft) or formed by various reactions involving water vapour (H_2O), nitrous oxide (N_2O), methane (CH_4) and halocarbons (CF_2, Cl_2, $CFCl_3$, CH_3CCl_3) which originate from the surface. The rates of some of the above reactions are temperature dependent, so a chemically inactive gas such as CO_2 can also alter ozone distributions through radiatively induced changes in atmospheric temperature. Many of the above processes are summarized in Fig. 1.

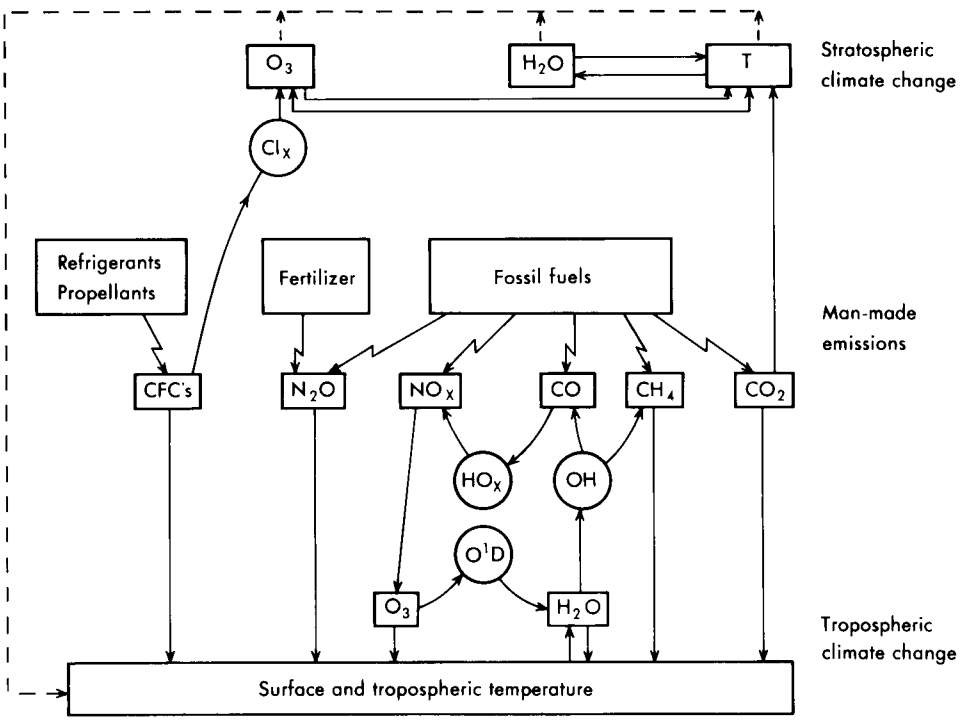


Figure 1. Climate–chemical interactions due to trace gases (adapted from Ramanathan 1980).

3. A brief survey of atmospheric pollutants

Carbon dioxide (CO_2)

The concentration of atmospheric carbon dioxide has increased from about 315×10^3 to 340×10^3 ppb (parts per American billion, or 10^9, by volume) since 1958. This increase is attributed to the burning of carboniferous fuel (coal, gas, oil) which releases carbon dioxide into the atmosphere directly. In fact, only about half the CO_2 released in the burning of fossil fuel appears to have remained in the atmosphere; the remainder is believed to have been absorbed by the ocean.

Attempts to forecast the changes in concentration of atmospheric CO_2 over the next 100 years or so have been made by first estimating the world's energy requirements over the next century, and then postulating what fraction will be produced by burning fossil fuels; the resulting concentration of atmospheric CO_2 has usually been estimated by assuming that a fixed fraction remains airborne.

However, as living organisms both absorb and release CO_2 this may be too simple an approach and, alternatively, one can attempt to predict the uptake of CO_2 by the oceans and the biosphere in detail. As there is much uncertainty in both the projected use of fossil fuels and the partition of the resulting CO_2 between the atmosphere and the rest of the carbon cycle, it is not surprising that there is a wide range of concentrations predicted for future atmospheric CO_2. A typical forecast is that CO_2 will reach 600×10^3 ppb in the next 70 or 80 years, or about a doubling of the estimated pre-industrial level.

CO_2 absorbs long-wave radiation at wavelengths near 15×10^{-6} m. Although CO_2 is by far the most abundant of atmospheric pollutants, the effect of a doubling is relatively small since with the present concentrations of CO_2 and water vapour most of the radiation near this wavelength is already absorbed by the atmosphere. Simple one-dimensional models suggest a doubling of CO_2 concentrations will produce an increase of 2 K in global mean surface temperatures (Table I). Results from more complex but still incomplete three-dimensional models predict changes of just over 2 K, although one study predicted a rise of 3.5 K (National Academy of Sciences 1982). On this basis the expected warming over the last century would have been about 0.3 K, but this would have occurred within much larger variations due to other natural causes. As yet a CO_2 signal cannot be identified with confidence.

Table I. *Estimates of global mean change in surface temperature due to increasing the concentration of various trace gases, ignoring atmospheric chemistry (World Meteorological Organization 1982).*

Gas	Mixing ratio (ppb)		Surface temperature change (K)
	Reference	Perturbed	
*CO_2	330×10^3	660×10^3	2.0
*N_2O	300	600	0.3–0.6
CH_4	1500	3000	0.3
*$CFCl_3$	0	1	0.15
*CF_2Cl_2	0	1	0.13
SO_2	2	4	0.02
O_3 (troposphere)	$F(\phi, z)$	$2F(\phi, z)$	0.9
O_3 (stratosphere)		25% decrease	0.5
H_2O (stratosphere)	3×10^3	6×10^3	0.6

* Clear evidence of increased tropospheric abundance of these gases. Water vapour feedback included implicitly. $F(\phi, z)$ denotes the distribution of ozone with latitude and height.

Nitrous oxide (N_2O)

Measurements by Weiss (1981) indicate that the tropospheric concentration of N_2O may have increased by 4% since 1963. Weiss suggests that most, if not all, of the increase is due to the burning of fossil fuels, though some may be due to fertilizer nitrification. More extreme estimates suggest that the N_2O concentration could double by the end of the next century. Nitrous oxide absorbs radiation over several wavebands including one centred on 7.8×10^{-6} m near the edge of the atmospheric window, so although its present abundance is only about 300 ppb, a thousand times less than that of CO_2, one-dimensional models predict a 0.3 to 0.6 K rise in temperature with a doubling of N_2O concentration, compared with the 2 K expected on doubling the concentration of CO_2.

Chlorofluoromethanes (Freon 12 and Freon 11; CF_2Cl_2 and $CFCl_3$)

Although present concentrations of Freons are small (about 0.1 ppb) they are of interest because of their long lifetime in the atmosphere and their part in the catalytic destruction of ozone. They also have strong absorption bands in the atmospheric window. The observed increases of about 10% a year agree

well with figures from industrial production, the only source. It has been speculated that concentrations will increase by a factor of 20 over the next century, causing a temperature rise of 0.5 to 0.6 K (World Meteorological Organization 1982).

Methane (CH_4)

Methane is a naturally occurring gas which absorbs infra-red radiation near the atmospheric window. Its present concentration is about 1.7 ppb and there is some evidence that it has been increasing in recent years, though it is not understood why. Model results suggest a doubling of methane concentration would increase global surface temperature by about 0.3 K.

Ozone (O_3)

Ozone absorbs incoming ultraviolet radiation, preventing radiation at wavelengths which are harmful to biological processes from reaching the surface. For example, there is some evidence that excessive exposure to ultraviolet radiation can cause skin cancer.

The concentration of ozone varies with height, latitude and season. However, the effectiveness of ozone as a shield against ultraviolet radiation is a function only of the amount of ozone between the top of the atmosphere and the earth's surface, referred to as the column density.

Early investigations on ozone concentrations were concerned with the possible reduction of stratospheric ozone by pollutants from stratospheric aircraft and, more recently, from Freons released from aerosol cans. Freons can lead to the catalytic destruction of ozone (that is, they can bring about the destruction of an ozone molecule without being changed themselves; one molecule of pollutant can take part in the destruction of many ozone molecules). The estimates of the change in column density with a given increase in Freon concentration have varied considerably over the last decade as our knowledge of the relevant stratospheric chemistry has increased. Latest estimates (World Meteorological Organization 1982) suggest that the ozone column density is not likely to be reduced by more than a few per cent. Nevertheless, the results from numerical models indicate that ozone concentrations would decrease in the upper stratosphere but increase in the lower stratosphere. As ozone also absorbs long-wave radiation strongly in the atmospheric window, this change in the vertical distribution would lead to a slight increase in surface temperature. Ten per cent of atmospheric ozone occurs in the troposphere. A doubling of tropospheric ozone would increase the earth's global mean surface temperature by about 0.9 K. It should be noted that the chemistry of ozone is dependent on temperature, so that an increase in CO_2 which would cool the stratosphere would also increase the concentration of ozone (for example, Groves *et al.* 1978).

Water vapour

Water vapour is not normally regarded as a pollutant. It is included since it absorbs long-wave radiation at most wavelengths. The amount of water vapour which the atmosphere can hold increases rapidly with temperature. Any change which warms the lower atmosphere is likely to increase the concentration of water vapour, producing a further atmospheric warming. This is often referred to as the 'water vapour feedback'. Changes in water vapour concentrations can also alter the levels of tropospheric ozone by perturbing the chemical equilibrium.

Particulate matter

Small particles suspended in the atmosphere (aerosols) may perturb the fluxes of both solar and long-wave radiation in the atmosphere. Dittberner (1978) estimated that about a third of the aerosols released in the atmosphere originate from man's activities, including the burning of fossil fuels and agriculture.

As the typical lifetime of a tropospheric aerosol is only a few days, the concentration of 'anthropogenic' aerosols falls off sharply away from regions of industrial and agricultural activity. It is difficult to obtain evidence of a long-term trend in aerosol concentrations because of the large temporal and spatial variabilities. The effect of aerosols on climate depends on the size and shape of the particles, their radiative properties and vertical distribution. An aerosol layer both reflects and absorbs solar radiation. The aerosol layer becomes warmer but the surface receives less radiation and cools. Kellogg (1977) has suggested that an increase in aerosol over a highly reflective surface such as the Arctic will produce a local warming, whereas over a dark surface it will lead to cooling. In short, the effect of man-made aerosols on global climate is uncertain and likely to be small. There is evidence that volcanic aerosols which reach the stratosphere where they persist for several months may influence global mean surface temperatures (for example, Hansen *et al.* 1978).

Summary

The above list is far from complete but it includes constituents which are more likely to affect the earth's climate. A more complete account is given by the World Meteorological Organization (1982). The main point is that the size of the effect depends not only on the concentration of the pollutant but also on the wavelength at which it absorbs radiation, the strength of the absorption and its lifetime in the atmosphere.

4. Simple models of climate

Most of the predicted changes in global mean surface temperature described in the previous section were obtained using simple climate models consisting of a single atmospheric column with globally averaged conditions. In this section the physical processes represented in such models are described and the limitations of the model results are emphasized.

The earth's surface is heated by solar radiation and cooled by the emission of long-wave radiation, and the loss of heat to the atmosphere through conduction, or evaporation of moisture (Fig. 2.). The atmosphere is cooled by long-wave radiation and heated by conduction from the surface, and by latent heat released during the condensation of water vapour evaporated from the surface. Heat and moisture are transported from the surface and distributed throughout the troposphere by vertical atmospheric motions (convection), producing a global mean reduction of temperature with height (lapse rate) of about 6 K km^{-1}.

A radiative convective model mimics these processes at a set of levels in the atmospheric column, known as grid points. The radiative heating or cooling is calculated by solving the standard equations of radiative transfer at each level in the atmosphere. The redistribution of heat and moisture from the surface is accomplished by not allowing the reduction of temperature with height to exceed some observed value (for example, the global mean) or by attempts to represent the vertical redistribution of heat more explicitly. (More sophisticated models may incorporate the effects of ozone chemistry.) The change in surface temperature due to an increase in the concentration of a given gas may be found by running the model to equilibrium with the present-day and perturbed vertical distributions of absorbing gases.

These models are relatively cheap to construct and use and can provide valuable insight into the physical processes through which pollutants may affect climate. For example, if the concentration of CO_2 in a typical atmospheric profile is doubled, there is an instantaneous increase of 1 to 2 W m^{-2} in the downward flux of radiation at the surface (Ramanathan 1981). This is small compared with the ambient fluxes which are of the order of 100 W m^{-2} (Fig. 2). If the atmospheric profile is allowed to respond radiatively (ignoring the expected increase in the transfer of heat from the surface) the troposphere

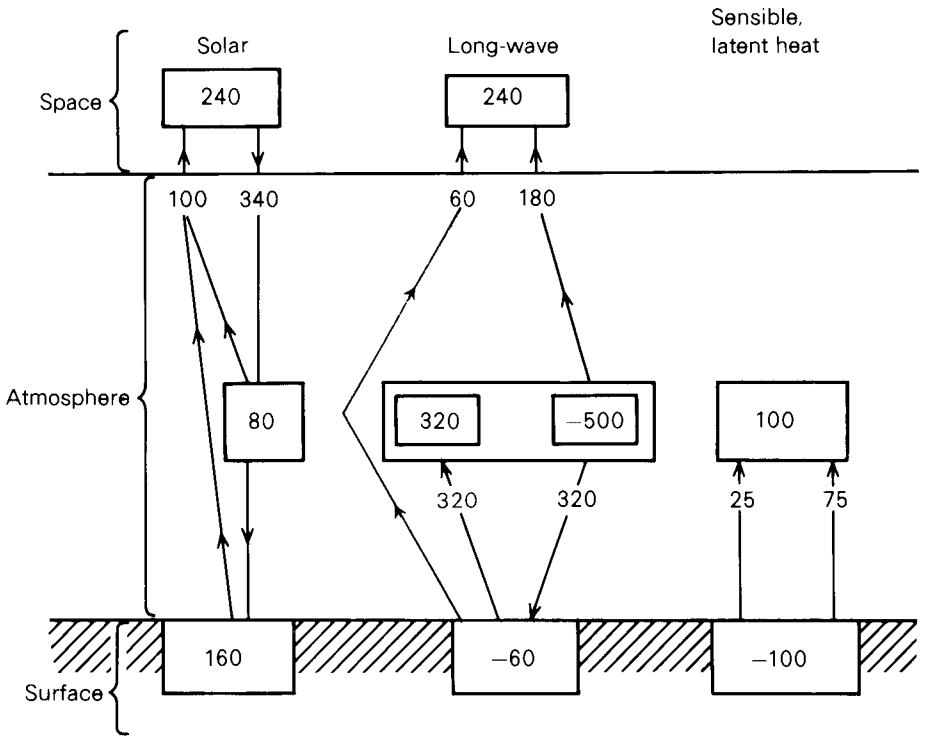


Figure 2. Simplified heat balance of the earth and atmosphere. The figures are derived from satellite observations and general circulation model results, and should be regarded as only approximate. Units are W m^{-2}.

warms and the downward flux of long-wave radiation increases by 3 W m^{-2}. If the changes at the surface are allowed to feed back to the atmosphere, there is a further increase in surface heating of about 12 W m^{-2}, largely through the water vapour feedback discussed earlier. The associated changes in surface temperature are given in Table II. This shows that doubling CO_2 produces a small perturbation in the atmospheric heat balance, which is amplified by several positive feedbacks.

Table II. *Effect of doubling CO_2, with and without feedbacks, in a radiative convective model (Ramanathan 1981).*

	No feedback	Radiative warming of troposphere	Surface, water vapour feedbacks
Effect on troposphere	3 W m^{-2} warming	Increased temperature	Increased temperature, humidity
Surface flux increase (W m^{-2})	1.2	3.5	15.5
Surface temperature change (K)	0.17	0.5	2.2

In the example above it was assumed that the relative humidity of the atmosphere remained unchanged. Results from another single-column model (Rowntree and Walker 1978) demonstrate the sensitivity of results to this and other assumptions. If the water vapour content (absolute humidity) of the atmosphere is held constant, doubling CO_2 produces an increase of 1.29 K, whereas making the water vapour concentration increase with temperature by fixing relative humidity produces almost twice the effect. Neither assumption is correct, though the second assumption is generally felt to be more realistic. Other choices will affect the magnitude of the response. For example, the response due to doubling CO_2 is smaller when cloud is included in the model than when it is omitted (Table III). In low latitudes much of the increased heating received at the surface due to increasing CO_2 is transferred to the atmosphere by the evaporation of water vapour and released as latent heat. When this process is taken into account the temperature rise at the surface is smaller, and the rise in the atmosphere is larger than that found using the global mean lapse rate.

Table III. *Sensitivity of radiative convective model results to imposed assumptions (Rowntree and Walker 1978)*

Assumption	Temperature change on doubling CO_2 (K)
Fixed absolute humidity	1.29
Fixed relative humidity	
(a) No cloud	2.46
(b) Average cloud	2.20
(c) Average cloud, allowance for latent heat	1.40

Many of the factors governing climate, such as orography, ocean temperatures, winds, sea ice and land–sea contrast cannot be represented in a single-column model, nor can such a model predict the changes at a given location at a given season. At best, it can give a crude estimate of the likely change in global mean surface temperature. Three-dimensional models of climate have the potential to provide more detailed estimates of climate change which are required by agriculture and other industries.

5. Three-dimensional models

In a three-dimensional atmospheric general circulation model the values of temperature, humidity and wind are stored at points around the globe on a horizontal grid at several levels in the atmosphere. In the Meteorological Office 5-layer model these grid points are about 330 km apart, and the state of the atmosphere at a given instant is represented by 10^5 numbers (Corby *et al.* 1977). These values are updated time-step by time-step by solving the equations of motion and thermodynamics at each point, subject to the mass, heat and moisture of the system being conserved. The grid-point values are updated every 10 minutes, and it requires 15 minutes of central processing time on an IBM 360/195 to advance the model by one day.

There are many atmospheric processes which occur on scales much smaller than that of the horizontal and vertical grid (for example, convective precipitation) and so cannot be modelled exactly. Their effect is represented in simplified forms (parametrizations) which are based on observations of the real atmosphere, on laboratory experiments or on results from more detailed numerical models.

In principle, a general circulation model can be used to forecast the day-to-day development of individual disturbances from a given initial atmospheric state. As with numerical models which have

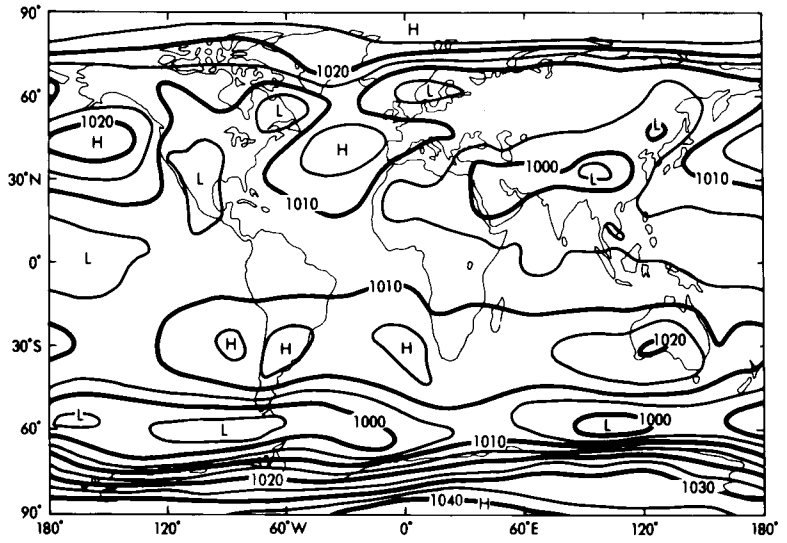
been specifically designed for such work, the accuracy of the forecast deteriorates with time until, after two or three weeks, the forecast fields contain little or no forecasting skill. For climate prediction, however, the models are run over much longer periods (months or even years) and the long-term mean behaviour of the simulations is studied. The climate of the model may be assessed by comparing the simulation obtained from a model with present-day sea surface temperatures, sea ice extents, CO_2 concentrations and so on, with climatological data. For example, the surface pressure pattern meaned over the final three northern summers of a four-year integration with the Meteorological Office 5-layer model (Fig. 3(a)) includes all the main features of the observed circulation (Fig. 3(b)), including the anticyclones centred over the winter continents and the summer oceans, the region of low pressure in the tropics which extends into the monsoon low over Asia, and the zone of low pressure over the southern ocean off Antarctica.

Estimates of the change in climate are found by comparing a simulation made with the standard model (the control integration) with a parallel simulation (the anomaly integration) in which only the relevant parameter (for example, the CO_2 concentration) has been changed. However, the model atmosphere, like the real atmosphere, shows an inherent year-to-year variability, so statistical tests must be carried out to show that the differences between the control and anomaly integrations are due to the changes in the model (in our example, the increase in CO_2) and are unlikely to have arisen by chance.

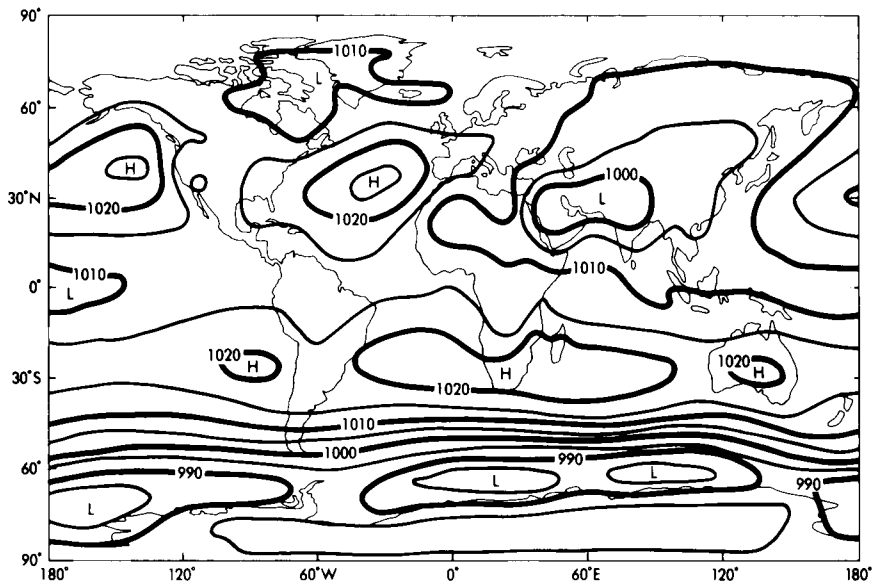
A full climate model should incorporate all the elements which contribute to climate, including the oceans and the continental ice sheets. Coupled ocean–atmosphere models are in their infancy and, as yet, the detailed interactions between the atmosphere and ocean and the major ice sheets have not been included in climate models. Hence, I will describe a few results from a model in which the continental ice sheets were held constant, sea ice extents were unchanged but a 2K increase in sea surface temperature was prescribed and CO_2 amounts were doubled (Mitchell 1983). The ocean temperature rise was chosen largely on the basis of single-column results.

The changes in surface temperature during winter (December to February) and summer (June to August) due to increasing CO_2 concentrations and sea surface temperatures, shown in Fig. 4, vary considerably with season and location. There are particularly large changes near 55°N in winter, which are due in part to the increased absorption of solar radiation by the land surface in the region where the model's snow line has retreated. The large rises over Scandinavia and north-western Russia, where there is little winter insolation, are due to increased westerly flow which has led to an increase in the frequency of occasions with winds off the warm ocean, and a decrease in the frequency of winds blowing from the centre of the cold Asian continent. In summer the largest rises (4–5 K) are found in the centre of the Eurasian continent. There is a noticeable minimum over western Europe, possibly due to the prevailing westerly flow (Fig. 3(a)) which carries air from an ocean which has been warmed by only 2 K. The variations in the seasonal changes are even more marked in precipitation (Fig. 5). In general, precipitation decreases over large areas of the subtropics, but generally increases in the inner tropics, along the eastern coasts of the summer continents, and over much of middle and high latitudes, particularly in the winter hemisphere. The broad zones of increased and reduced precipitation are further north during June to August, so that some regions are drier in the winter and wetter in the summer, and vice versa.

The assumption of a uniform increase in sea surface temperature is probably unrealistic, so a further integration has been performed in which the rise in sea temperatures increases with latitude, changes in high latitudes being over twice those at the equator (Mitchell and Lupton 1983). The changes in soil moisture (surface wetness) in this and the previous experiment are shown in Figs 6(a) and (b) respectively. Both experiments predict a drier land surface over most of North America and Eurasia between 30° and 60°N and a wetter surface over Mexico, south-east Asia and south-west Africa. Note that the predicted changes are inconsistent over the Sahara and the east of North America. These results



(a)



(b)

Figure 3. Pressure at mean sea level (isobars at 5 mb intervals).
(a) From Meteorological Office 5-level model, June, July and August.
(b) Observed, July (from Schutz and Gates 1972).

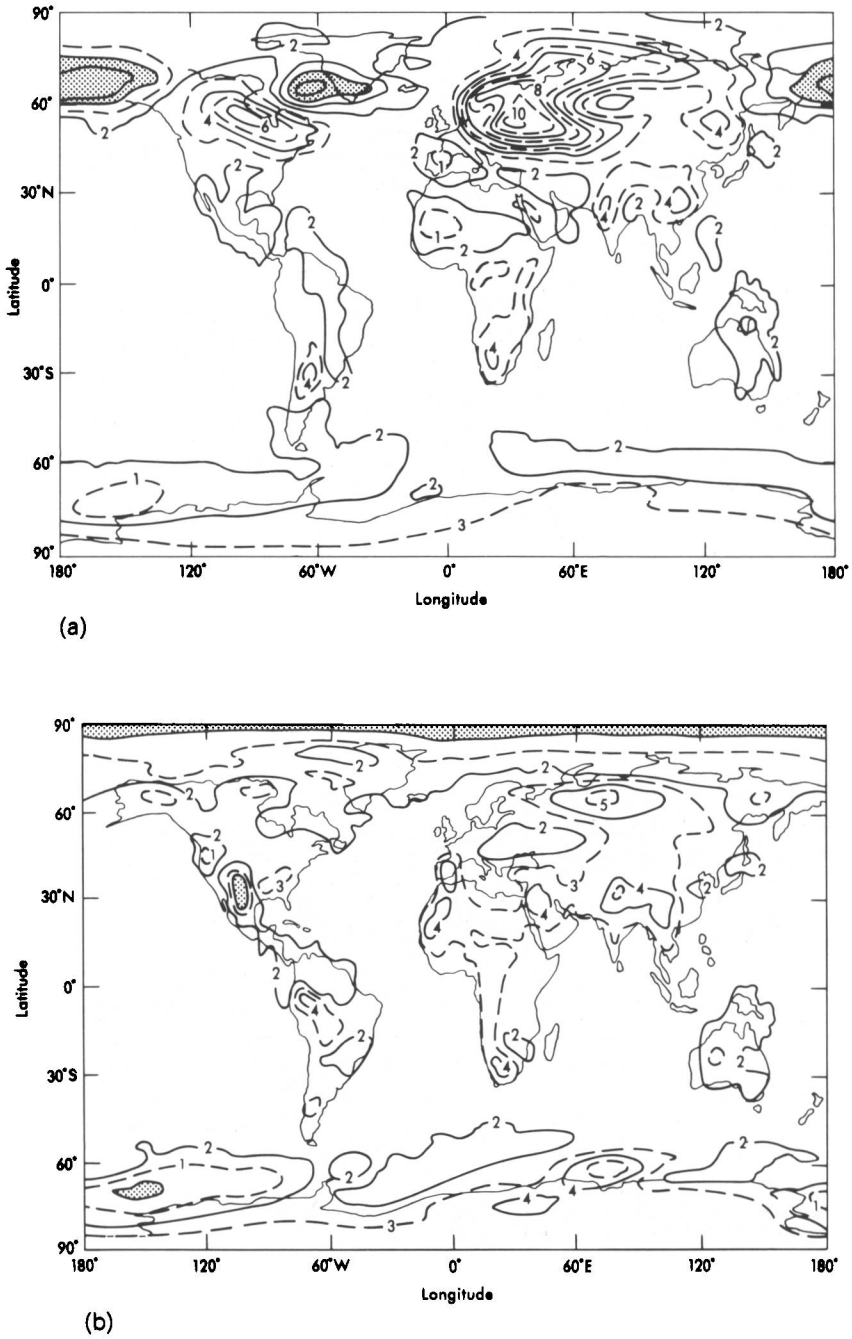


Figure 4. Changes in model surface temperatures due to doubling CO_2 and increasing sea temperatures by 2 K. Isopleths are drawn at 1 K intervals with odd-numbered isopleths indicated by dashed lines; areas of decrease are stippled.
(a) Winter (December, January and February).
(b) Summer (June, July and August).

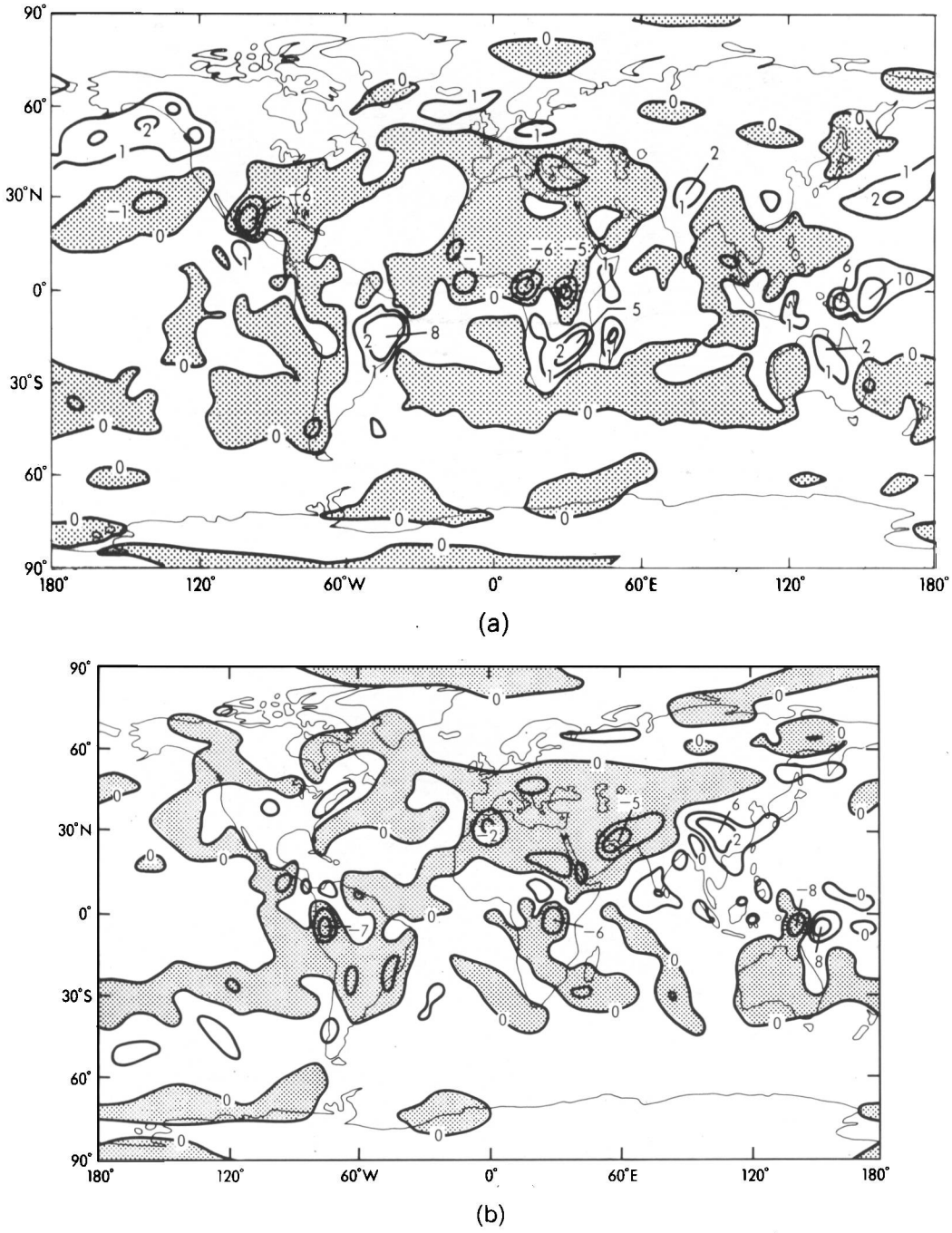


Figure 5. Changes in model precipitation due to doubling CO_2 and increasing sea temperatures by 2 K. Isopleths are drawn at 1 mm/day intervals; areas of decrease are stippled.
(a) Winter (December, January and February).
(b) Summer (June, July and August).

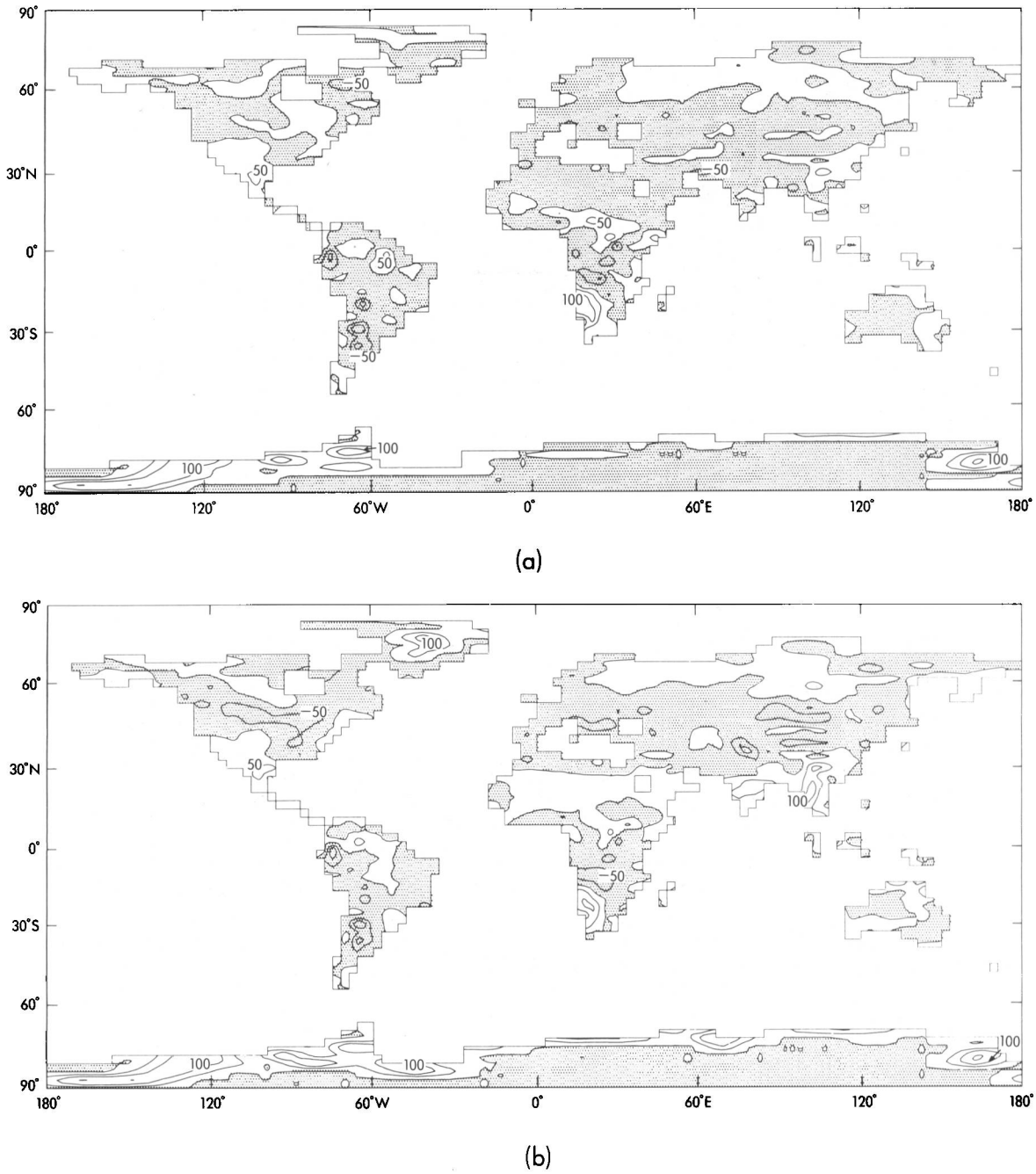


Figure 6. Changes in model soil moisture in summer (June, July and August). Isopleths are every 50 mm; areas of decrease are stippled.

(a) Due to doubling CO_2 and a uniform 2 K increase in sea temperatures.

(b) Due to quadrupling CO_2 and rises in sea temperature which increase with latitude. (Changes should be halved for comparison with Fig. 6(a)).

give some guide to the reliability of predicted changes in regional climate obtained to date. The only other published accounts of detailed seasonal changes in a climate model (Manabe and Stouffer 1980, Manabe *et al.* 1981) described the effects of quadrupling CO_2 in an atmospheric model coupled to a simple model of the upper ocean. Despite the difference in the models used, the changes in the hydrological cycle are generally similar to those described here.

6. Concluding remarks and summary

I have described in some detail the physical processes through which pollutants influence climate and how those processes are represented in numerical models of climate. Although the initial change in radiative heating due to increased pollutants is in most cases known with reasonable accuracy, the subsequent response of the atmosphere and other elements influencing climate is less well understood.

There are several ways in which our understanding of man's impact on climate is being advanced. The contribution from chemically active gases is continually being updated as measurements of concentrations and reaction rates are revised. The parametrization of physical processes in climate models is being improved through both observational studies and numerical experiments. The most recent climate models represent the ocean explicitly. The increase in computing power made available by the advent of vector computers will enable models with adequate horizontal resolution to be integrated over decades rather than years. Nevertheless, the problem of understanding climate and climate change will occupy atmospheric scientists for many years to come.

Measurements made over the last decade or so have shown that the concentration of certain trace gases is increasing. In most cases the increase can be attributed to man's activities. The increase in the concentration of those gases which are radiatively active is expected to raise the global mean surface temperature. The magnitude of the contribution of an individual constituent to this rise depends not only on the size of the increase in concentration but also on the gas's capacity to absorb long-wave radiation and the wavelengths at which it does so. The increase in chemically active constituents will alter the vertical distribution of ozone, though present estimates indicate that the total amount of ozone will not be greatly affected.

Many of the statements which have been made concerning the effects of pollutants on climate have been based on evidence from single-column models of the atmosphere. The results depend to a great extent on the assumptions made in the model and do not take into account many of the elements which govern climate. Even where three-dimensional climate models have been used to study the consequences of increased CO_2, considerable simplifications, particularly in the treatment of oceans and cloud, have been made. However, these studies do indicate that the changes accompanying a global warming would vary considerably with time of year and geographical location, and that changes in the hydrological cycle are likely to be as important as the changes in temperature.

Acknowledgements

I am grateful to Dr A. Tuck for drawing my attention to the most recent estimates of concentrations of trace gases and their potential effects, and to members of the Dynamical Climatology Branch, past and present, who have contributed to the development and running of the atmospheric general circulation model featured in this paper.

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Changes in the seasonal variation of temperature over the United Kingdom between 1861 and 1980

By S. G. Smith

(Meteorological Office, Bracknell)

Summary

Harmonic analysis of daily mean maximum and daily mean minimum temperatures has been performed for (i) five UK stations using data for 1901–30 and 1941–70 separately and (ii) for Oxford using data for ten overlapping 30-year periods between 1861 and 1980. Differences are observed between the different periods in the amplitudes of the first (annual) harmonic and the amplitude and phase of the second harmonic. These differences are interpreted in terms of changes in the seasonal variation of temperature.

1. Introduction

Some time ago the climatological research group in the Climatological Services Branch of the Meteorological Office were asked to give advice relating to the variation of temperature through the winter months. In the course of answering this enquiry it was found that 30-year means of daily temperatures failed to remove irregular day-to-day variations in the temperatures. The means also produced apparent warm or cold spells of several day's duration which were, in general, purely a function of the particular period chosen. These features are illustrated in Fig. 1, which is a plot of mean daily maximum temperatures at Oxford for 1 January to 17 February over the periods 1901–30 and 1941–70.

Harmonic analysis of the data was therefore undertaken to smooth out the 'noise' and this was considered to produce a more satisfactory description of the seasonal variation than the raw 30-year means. This form of analysis has been carried out by, amongst others, Craddock (1956a) who investigated the amplitude and phase of the first and second annual harmonics of monthly mean temperatures at 160 stations in the British Isles, using data for 1921–50. In a related paper (1956b) he fitted two-term annual harmonics to non-overlapping five-day means of daily temperatures at 42 stations in central and northern Europe. In both papers his primary interest was to determine the spatial patterns in the parameters, in particular relating variations in the phase of the second harmonic to changes in the seasonal variation of temperature.

In this paper harmonic analysis was performed on daily maximum and daily minimum temperatures from five United Kingdom stations using data for 1901–30 and 1941–70. The procedure was then repeated on Oxford data only for ten overlapping 30-year means between 1861 and 1980, the results of which are assumed to be applicable to the other four stations and indicate differences that can occur in the seasonal variation over different 30-year periods.

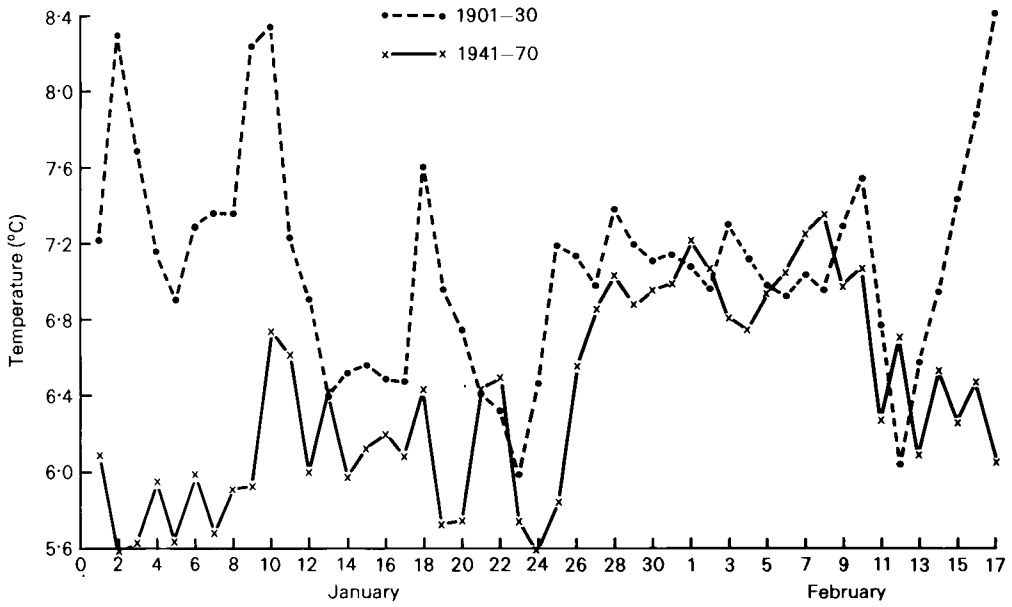

Figure 1. Mean daily maximum temperatures at Oxford for 1 January to 17 February, over the periods 1901–30 and 1941–70.

2. Data

Five widely scattered stations having almost unbroken daily maximum and minimum temperature records between 1900 and 1970 were selected for the first part of the analysis. These five are Plymouth, Oxford, Armagh, Durham and Gordon Castle, and their locations are shown in each of Figs 2–5. Minimum temperatures for Gordon Castle for October 1956 are missing and are therefore excluded. Temperatures are available for Oxford since 1853 and data for 1861 onwards have been used for the second part of the analysis.

With regard to the homogeneity of the observations, Smith (1978) found evidence for changes in the mean of the Plymouth maxima and minima series which may be due to the change of site between the Hoe and Mount Batten in 1930. There is also a possibility that the series for the other stations are not entirely homogeneous owing to minor changes of site or changes in observing hour, or both. However, since the main purpose of this study is to investigate changes in the variation of temperature within a year, these potential inconsistencies should not seriously affect the analysis.

3. Method of analysis

Future references to 'maxima' and 'minima' will denote the highest and lowest daily values. 'Peak value' will refer to the highest temperature attained by a harmonic in the regression model described below.

For each 30-year period and for each station, maxima and minima were averaged separately for each day of the year; 29 February was omitted, so each series comprised 365 terms. Each term y_t was assumed to follow an expression of the form

$$y_t = \bar{y} + \sum_{i=1}^{N} (a_i \cos ict + b_i \sin ict),$$

where $\bar{y}$ is the mean, a_i and b_i are the components of the ith annual harmonic (up to i=N), $c = 2\pi/365$ and t is measured in days from midnight on 31 December.

It was found that the first two harmonics accounted for over 95% of the variance of both the maxima and minima series and higher-order harmonics were therefore neglected.

The components of the first two harmonics were estimated using a least-squares regression program available in the BMDP statistical package (Dixon and Brown 1979). The amplitudes A_i and the phases ϕ_i were calculated from the components, where

$$A_i = (a_i^2 + b_i^2)^{1/2}$$

and

$$\phi_i = \arctan (b_i/a_i).$$

The date of the peak value of the first harmonic and the date of the summer peak value of the second harmonic were determined from ϕ.

4. Results

Results are presented in two sub-sections. Section 4.1 relates to analyses for the five stations over the periods 1901–30 and 1941–70. Section 4.2 considers Oxford data only for the longer period 1861–1980.

4.1 *Five stations, 1901–30 and 1941–70*

Table I presents means and variances of the y_t values together with amplitudes and phases of the first and second harmonics. For both maxima and minima the 1941–70 means are about 0.3 °C higher than the 1901–30 means, the exception being the Plymouth maxima (which may be due to the effects of site change). The general increase occurs despite the fact that January and February temperatures are lower in the 1941–70 period. The variances are also higher in the later period, which is mainly a reflection of the fact that there is a greater annual range of daily temperatures for 1941–70.

The standard errors of the amplitude and phase of the first harmonic have been derived from the standard errors of the components supplied by the BMDP regression program. That of the amplitude was found to be approximately 0.04 °C and that of the date of peak value 0.4 days, with the latter inversely proportional to the amplitude. The variance of the amplitude is given by $A^2/2$ where A is the amplitude. In the table this variance is expressed as a proportion of the variance of the series.

It is seen that the amplitude for maxima is 20–30% greater than for minima and the date of peak value occurs 8–11 days earlier. The result for the amplitudes is a measure of the greater annual range of maxima; that for the dates of peak value probably arises from the fact that:

(i) maxima are highly related to the amount of solar radiation received at the earth's surface and the maximum and minimum elevation of the sun occurs in June and December respectively, and

(ii) minima are governed more by the atmospheric dew-point which in turn is related, amongst other factors, to the earth and sea temperatures which reach their maximum and minimum after the solstices.

The proportion of variance of the daily means accounted for by the first harmonic increases slightly between 1901–30 and 1941–70 for maxima (except at Gordon Castle) and more substantially for minima. The peak value date for both variables remains fairly constant, the only appreciable change occurring for Plymouth minima.

Table I. *Summary data for each station and period.*

Station and period		Mean (°C)	Variance $(°C)^2$	First harmonic: Amplitude: Value (°C)	First harmonic: Amplitude: Variance as % of total	First harmonic: Phase: Date of peak value (day/month)	Second harmonic: Amplitude: Value (°C)	Second harmonic: Amplitude: Variance as % of total	Second harmonic: Phase: Date of summer peak value (day/month)
(a) Maxima									
Oxford	1901–30	13.68	28.14	7.42	97.8	19/7	0.55	0.54	13/8
	1941–70	13.89	31.14	7.82	98.2	20/7	0.43	0.30	8/9
Plymouth	1901–30	13.76	16.81	5.73	97.6	27/7	0.47	0.66	11/8
	1941–70	13.48	17.00	5.78	98.2	28/7	0.24	0.17	2/9
Armagh	1901–30	12.60	18.97	6.09	97.7	20/7	0.54	0.77	8/8
	1941–70	13.04	20.69	6.38	98.4	19/7	0.36	0.31	8/9
Durham	1901–30	11.85	23.43	6.76	97.5	22/7	0.63	0.85	8/8
	1941–70	12.38	26.22	7.17	98.1	22/7	0.43	0.35	4/9
Gordon Castle	1901–30	11.87	19.79	6.20	97.1	22/7	0.55	0.76	9/8
	1941–70	12.07	21.41	6.43	96.5	22/7	0.41	0.39	6/9
(b) Minima									
Oxford	1901–30	5.96	14.73	5.27	94.3	28/7	0.94	3.00	29/7
	1941–70	6.28	17.44	5.82	97.2	28/7	0.50	0.72	7/8
Plymouth	1901–30	7.66	12.09	4.78	94.5	1/8	0.82	2.78	28/7
	1941–70	7.89	12.20	4.86	96.8	5/8	0.34	0.47	5/8
Armagh	1901–30	5.39	11.22	4.56	92.5	31/7	0.98	4.28	27/7
	1941–70	5.68	12.77	4.96	96.2	30/7	0.48	0.90	12/8
Durham	1901–30	4.50	13.67	5.07	94.0	31/7	0.97	3.44	1/8
	1941–70	4.83	15.13	5.43	97.4	31/7	0.42	0.58	11/8
Gordon Castle	1901–30	4.45	11.42	4.64	94.3	29/7	0.89	3.47	27/7
	1941–70	4.82	13.41	5.11	97.3	30/7	0.39	0.57	9/8

Figs 2–5 show, for the first harmonic in 1941–70, the variation across the country of the amplitude (Figs 2 and 3) and date of peak value (Figs 4 and 5) for maxima and minima. The spot values shown are those for the five stations given in Table I; the isopleths are based on the pattern of variation observed by Craddock (1956a) but it would be unwise to infer absolute values from Figs 2–5 alone.

For the second harmonics, the standard error of the amplitude is again about 0.4 °C but the date of peak value approximately 2 days, with its magnitude inversely proportional to the amplitude. The variance explained for maxima is less than 1% of the total and shows a decrease from 1901–30 to 1941–70. For minima the amount explained is about 3.5% in 1901–30 but drops to below 1% in 1941–70. The phase of the second harmonic has also altered considerably, particularly for maxima. The date of peak value for maxima occurs about one month later in the 1941–70 period and 11 days later for minima, compared to 1901–30. These findings are discussed in Section 5.

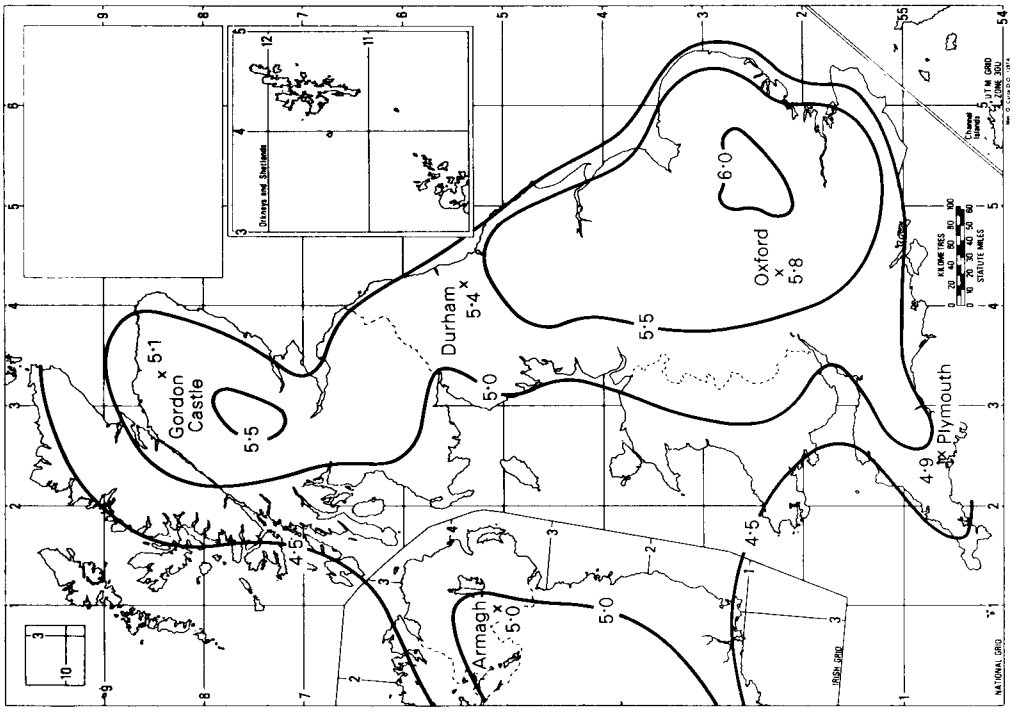

Figure 3. Minima 1941–70. Amplitude of first harmonic (°C).

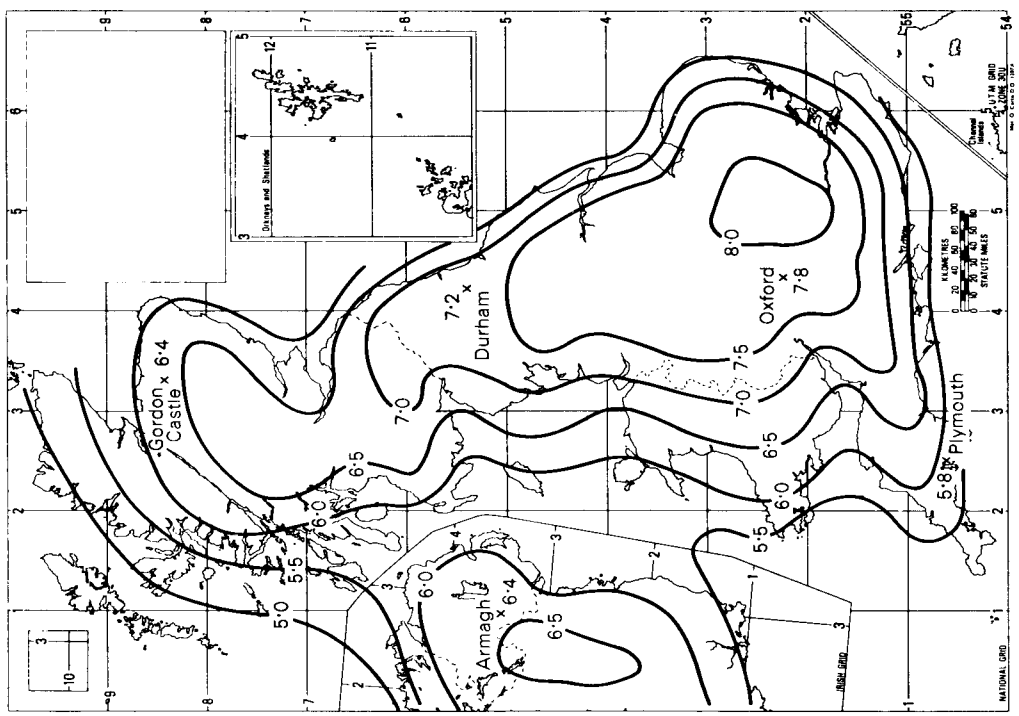

Figure 2. Maxima 1941–70. Amplitude of first harmonic (°C).

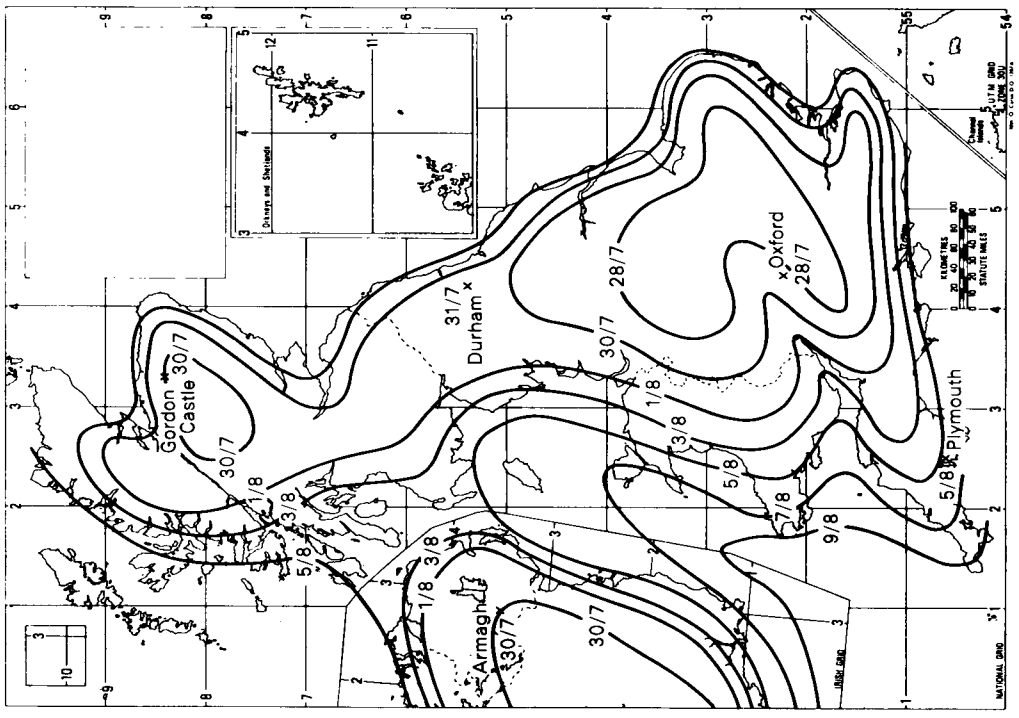

Figure 5. Minima 1941–70. Date of peak value for first harmonic (day/month).

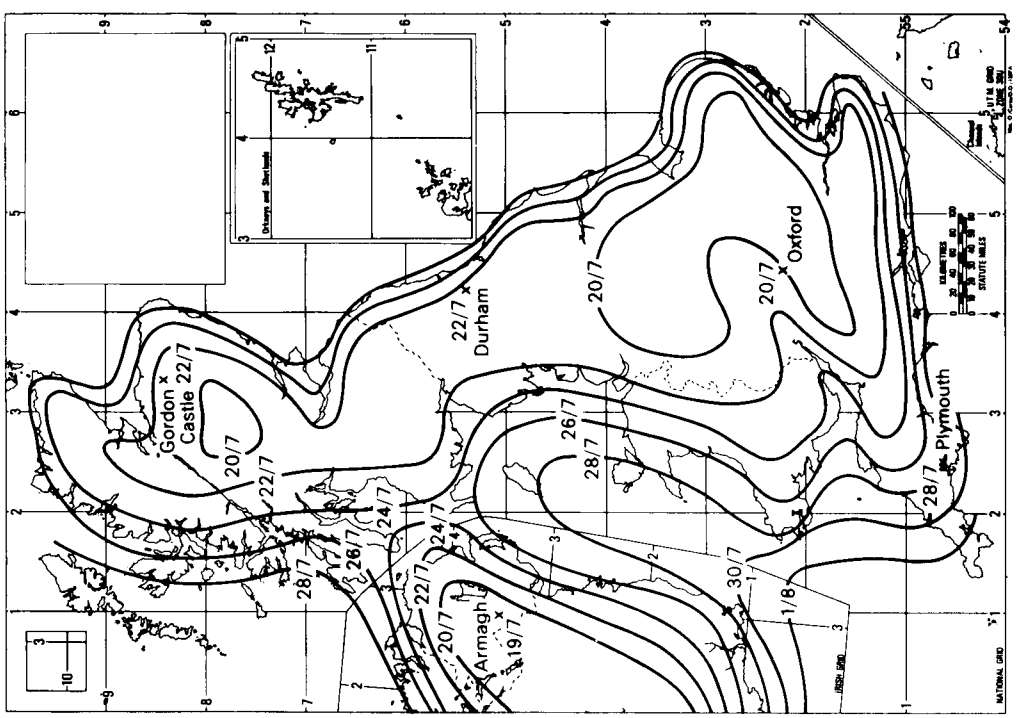

Figure 4. Maxima 1941–70. Date of peak value for first harmonic (day/month).

4.2 *Oxford 1861–1980*

To relate changes in the magnitude and phase of the harmonics between 1901–30 and 1941–70 to other periods the analysis of 4.1 was repeated for the periods 1861–1890, 1871–1900, ... 1951–80 for Oxford data. The results of the previous sub-section showed little deviation from station to station in regard to the differences between 1901–30 and 1941–70. It is therefore assumed that results for Oxford presented below can be considered representative of the other four stations and indeed of the United Kingdom as a whole.

Various statistics are presented for the different periods in Table II. For maxima, the mean increases between 1881–1910 and 1921–50 followed by a decline. The variance reaches its maximum in 1941–70. For minima, the mean increases monotonically after 1881–1910 but for the variance the variation with time is more complex.

Table II. *Summary data for Oxford.*

			First harmonic			Second harmonic		
			Amplitude		Phase	Amplitude		Phase
Period	Mean (°C)	Variance $(°C)^2$	Value (°C)	Variance as% of total	Date of peak value (day/month)	Value (°C)	Variance as % of total	Date of summer peak value (day/month)
(a) Maxima								
1861–90	13.57	31.87	7.91	98.1	18/7	0.66	0.68	15/8
1871–1900	13.51	31.06	7.79	97.8	18/7	0.72	0.83	17/8
1881–1910	13.46	29.80	7.65	98.3	19/7	0.55	0.51	20/8
1891–1920	13.63	29.32	7.59	98.3	18/7	0.47	0.38	16/8
1901–30	13.68	28.14	7.42	97.8	19/7	0.55	0.54	13/8
1911–40	13.92	29.03	7.53	97.7	19/7	0.61	0.64	14/8
1921–50	14.12	30.32	7.70	97.8	19/7	0.68	0.76	16/8
1931–60	14.10	31.07	7.81	97.9	19/7	0.53	0.45	27/8
1941–70	13.89	31.14	7.82	98.2	20/7	0.43	0.30	8/9
1951–80	13.73	29.78	7.66	98.5	21/7	0.39	0.26	22/8
(b) Minima								
1861–90	5.83	15.65	5.45	94.7	27/7	0.82	2.15	3/8
1871–1900	5.78	16.25	5.56	95.2	28/7	0.93	2.66	30/7
1881–1910	5.77	15.88	5.52	96.1	29/7	0.79	1.97	26/7
1891–1920	5.91	15.23	5.40	95.7	28/7	0.85	2.37	26/7
1901–30	5.96	14.73	5.27	94.3	28/7	0.94	3.00	29/7
1911–40	6.04	15.37	5.41	95.1	27/7	0.91	2.69	28/7
1921–50	6.12	16.79	5.67	95.8	28/7	0.78	1.81	31/7
1931–60	6.21	17.51	5.82	96.8	28/7	0.61	1.06	29/7
1941–70	6.28	17.44	5.82	97.2	28/7	0.50	0.72	7/8
1951–80	6.29	16.71	5.70	97.1	29/7	0.54	0.87	2/8

Considering the first harmonic, the proportion of variance and the phase for maxima are relatively constant although some differences emerge for the most recent periods. For minima the phase is constant but the proportion of variance decreases until 1901–30 then increases.

In the results for the second harmonic the proportion of variance for maxima is highest in 1921–50 and has fallen since then. The date of peak value is earliest in 1901–30 and latest in 1941–70, the two periods considered in 4.1. For minima, these same two periods almost yield the two extremes for the proportion of variance and the date of peak value.

5. Interpretation of results

It has been shown that between 1861–90 and 1951–80 some large differences occurred in the proportion P_1 of the variance accounted for by the first harmonic and the corresponding quantity P_2 and date of peak value D_2 for the second harmonic. A period in which P_1 is relatively large and P_2 relatively small (for example 1941–70) has, on average, a seasonal variation in temperature more closely resembling a pure sine curve than a period for which the reverse is true, e.g. 1901–30. If D_2 is later in the year for one period than another (up to a maximum of 45 days later), as it is in 1941–70 relative to 1901–30, the winter trough is more pronounced and the summer peak extends later into the year, with a consequent decrease in length of the autumn season. These effects are displayed diagrammatically in Craddock (1956a).

It was decided to study the results in quantitative terms by comparing, for the periods 1901–30 and 1941–70, plots of daily values through the year generated from their respective means and first two harmonics only. These periods were chosen because in general they give the most extreme results, in opposite senses, for the phases and magnitudes of the harmonics. Plots for maxima and minima are given in Fig. 6; note that only values every fifth day are shown. It is observed that the features discussed above can be identified and that for maxima the greatest difference between the two curves is just under 1 °C (in the autumn). The same is true for minima but the differences are more pronounced with the greatest discrepancy between the two curves about 1 °C again occurring in the autumn. However, it is noted from Table I that the mean temperature difference (1941–70 minus 1901–30) is 0.2 °C for maxima and 0.3 °C for minima. If one therefore considers the differences in the seasonal variation with these mean differences removed, the maximum difference takes place in midwinter, equal to about 0.8 °C for maxima and 1.0 °C for minima.

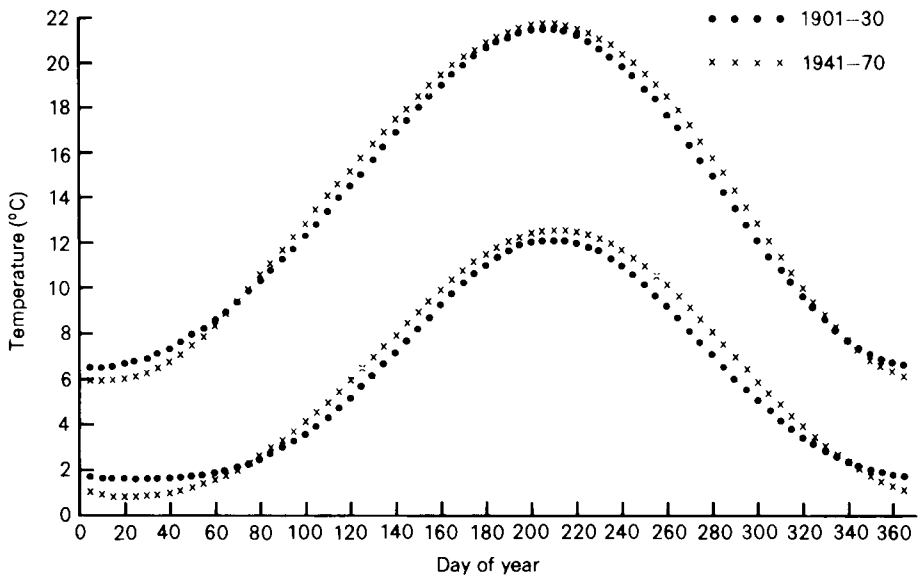

Figure 6. Generation of seasonal variation of maxima and minima from the means and first two annual harmonics for Oxford. (Points are plotted for every fifth day.)

6. Conclusion

Harmonic analysis of UK daily maximum and minimum temperatures averaged over different 30-year periods has shown some statistically significant differences in the amplitude of the first harmonic and the amplitude and phase of the second harmonic. When results are compared for the periods 1901–30 and 1941–70, the effect is observed to give a shorter but sharper winter for the later period, a summer which extends later into the year and a shorter autumn. In terms of temperatures, if differences in the annual mean are removed the greatest difference in the seasonal variation occurs in midwinter where 1941–70 averages are about 0.8–1.0 °C less than the 1901–30 values.

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The mystery of the missing bronze plaques

By R.P.W. Lewis

(Meteorological Office, Bracknell)

In 1911 the Director of the Meteorological Office (Dr Napier Shaw, as he then was) planned a series of bronze plaques for the entrance hall at the top of the main staircase in the new building at South Kensington, commemorating five distinguished meteorologists who had been intimately associated with official British meteorology. The three tablets were executed by the Bromsgrove Guild who also made the wooden plaques bearing the Meteorological Office emblem with interlaced MO letters, a rising sun and a weathercock (Lewis 1978)*. A short leading article in *Symons's Meteorological Magazine* for January 1912 stated:

> We reproduce in the frontispiece to this volume a photograph of the three tablets, which were executed by the Bromsgrove Guild, which is to be congratulated on the simple effectiveness of the work. The actual size of each is about 21 inches in length and 8 inches in height. We understand that casts in bronze of any of the medallions can be obtained from the Guild, for the price of £2.2s. each.
>
> First in date comes Admiral FitzRoy, who was the first Official Meteorologist in this country, and presided over the Meteorological Department of the Board of Trade from 1854 to 1865. No more enthusiastic pioneer in meteorology ever lived in this country, and no more fitting effigy than his could appear on the walls of the new Meteorological Office.
>
> The next plaque commemorates the Meteorological Committee of the Royal Society, which was responsible for the Meteorological Office from 1867 to 1877, and bears the heads of Lieutenant-General Edward Sabine, Chairman of the Committee, and of Dr. R. H. Scott, Director of the Office during this period. Dr. Scott is thus placed in the proud position of being honoured in his lifetime by a monument if not "more durable than brass," at least as enduring.

*Lewis. R.P.W.; The Meteorological Office badge. *Meteorol Mag*, **107**, 1978, 338–339.

The third records the Meteorological Council, with portraits of Professor Henry J.S. Smith, who was Chairman of the Council from 1877 to 1883 and of Sir Richard Strachey, perhaps the most successful of them all, who succeeded him and continued in office to the beginning of the new order in 1905.

(The frontispiece referred to is here reproduced as Fig. 1.)

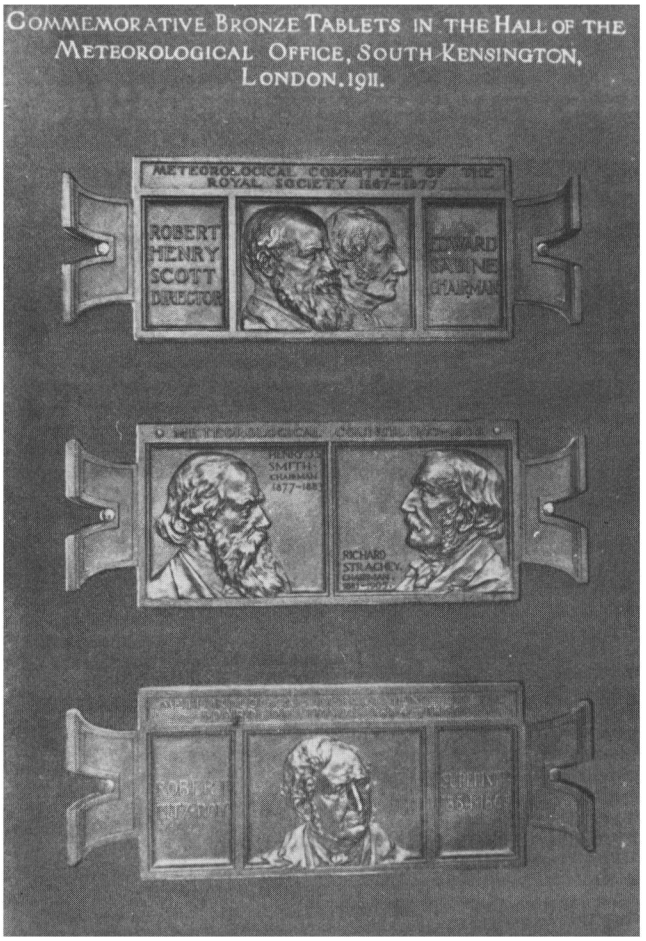

COMMEMORATIVE BRONZE TABLETS IN THE HALL OF THE METEOROLOGICAL OFFICE, SOUTH KENSINGTON, LONDON. 1911.
ROBERT HENRY SCOTT DIRECTOR
RICHARD STRACHEY

Figure 1

The plaques remained in place in the South Kensington building until the Second World War. After the war it seems that they were placed on display in the conference room in Victory House, Kingsway, the principal Meteorological Office Headquarters until the move to Bracknell in 1961. Since that time they have been lost, probably having disappeared during the move. An attempt was made a few years ago to trace their whereabouts but was unsuccessful, possibly because by that time everyone who had been actively concerned with implementing the move was dead. Perhaps they are still languishing in a packing case in a store-room on some remote airfield. We shall be glad to hear from anyone who can provide either a clue, or a replacement set originally purchased for six guineas by his grandfather.

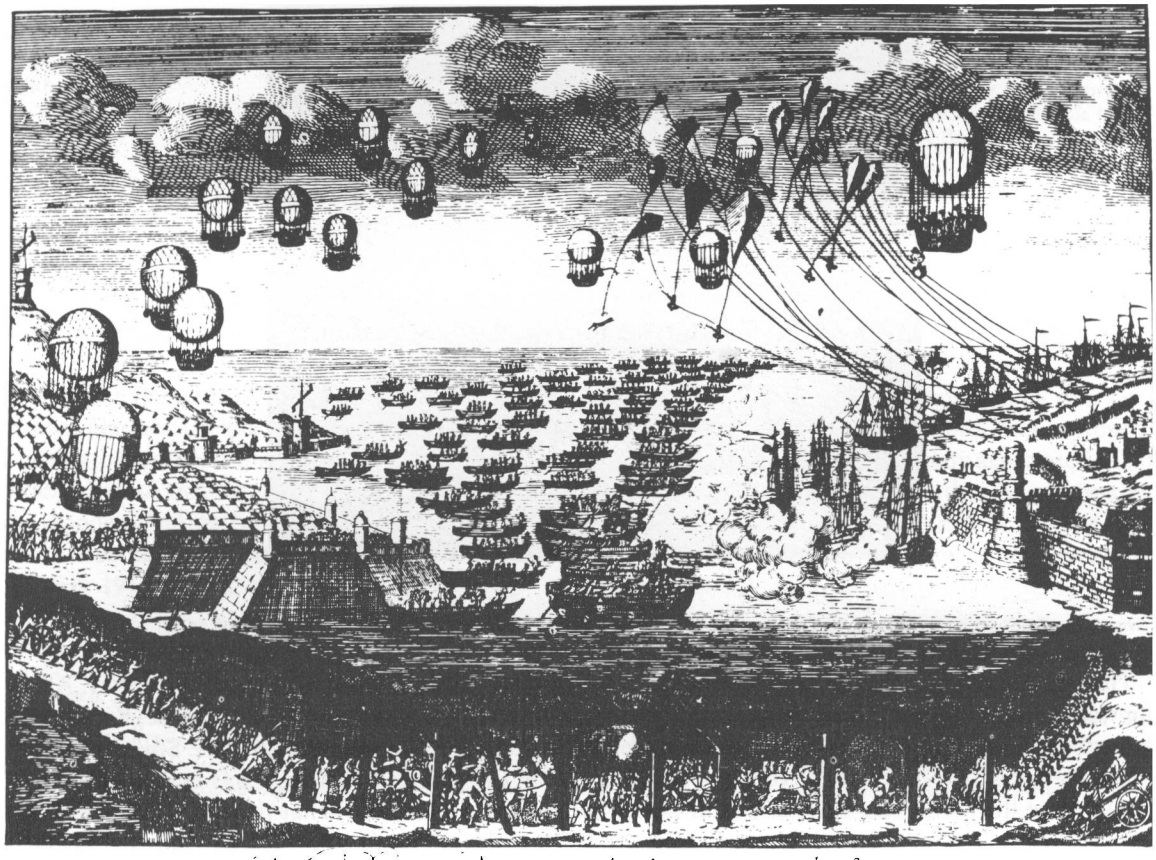
Notes and news

75 years ago

The following extract is taken from *Symons's Meteorological Magazine,* January 1909, **43,** 225–226.

THE MASTERY OF THE AIR.

The year 1908 will be memorable in history as that which saw the art of aërial navigation or aviation perfected so far as to pass from the advanced experimental to the rudimentary practical stage. It had long been recognised that movement through the air can be effected by two types of machine, one lighter than air, *i.e.,* of the nature of a balloon, in which the problem is one of propulsion and steering only; the other heavier than air, in which the motive power must not only drive the machine forward, but maintain its position against the force of gravity. The latter, or aëroplane type, is essentially a kite, which instead of being lifted by the rush of air acting against the resistance of the surface held by the string, is lifted by the rush of the surface driven by a motor against the resistance of the relatively stationary air. The



Divers Projets sur la descente en Angleterre

success of this type depended mainly on the construction of a motor which was sufficiently powerful and sufficiently light, and the provision of such a motor is the direct result of the development of internal combustion engines for road locomotion.

In 1908 Count Zeppelin's great balloon airship achieved the unprecedented feat of performing a whole day's journey in the air — the unhappy wreck of the vessel in no way detracted from the epoch-making nature of the cruise. In 1908 also Mr. Wilbur Wright, in an aëroplane of the heavier than air type and of the simplest possible construction, achieved the more remarkable feat of flying 77 miles in 2 hours 20 minutes without touching the ground, and with perfect control of movement both horizontal and vertical. The rest is merely the development of proved possibilities, and no doubt can be felt that within the next few years aviation will be one of the most pressing of practical problems.

Already questions are being asked as to how the law can be adapted to regulate aërial traffic, and no doubt the military authorities of all countries have been busy devising new methods of attack and defence. One of our German friends, as a gentle satire on the dread of invasion (which some portions of the British press have almost persuaded the less enlightened members of the foreign public to believe is a brooding terror in this country) sent us by way of a Christmas card a copy of the curious French engraving, dated 1804, which we reproduce as a frontispiece to this volume. It depicts various plans supposed to have been worked out in Napoleon's camp at Boulogne when the invasion of England was nearer than it has been since, and it is curious to notice that the Channel tunnel — itself one of the bogies of the twentieth century — was there, and that the troop-balloon was to be hurled against our country only to be met by a corps of gallant riflemen, each suspended to the tail of a man-lifting kite.

Though there is no new thing under the sun in popular scares or scientific imagination, there will undoubtedly follow a vast impetus to meteorology, leading to the discovery of many new facts, as a result of the opening of the fields of the air to the activity of man, and for many years to come the advancement of our science and the perfecting of the art of aviation will progress by mutually benefiting each other.

A.C. Wiin-Nielsen awarded Wihuri International Prize

Professor A.C. Wiin-Nielsen, Secretary-General of the World Meteorological Organization, received the prestigious Wihuri International Prize in Helsinki on 9 October 1983. He is the first meteorologist to be awarded this honour.

The Wihuri Foundation for International Prizes was established in 1953 to promote and sustain the cultural and economic development of society by distributing international prizes. The Wihuri Sibelius Prize, named after its first recipient, is awarded for distinction in the field of music. The Wihuri International Prize is awarded to individuals, groups or organizations for contributions to a much broader concept of cultural and economic development. Since 1953, 17 Prizes have been awarded — 9 Wihuri Sibelius Prizes and 8 Wihuri International Prizes — the last one in 1979.

Professor Aksel C. Wiin-Nielsen, Secretary-General of the World Meteorological Organization from 1980 to 1983, was born in 1924 in Klakring, Denmark. After taking his degree in Mathematics, Physics, Chemistry and Astronomy at the University of Copenhagen, Denmark, he joined the Meteorological Institute of Denmark in 1952 as a Scientific Officer. From 1952 to 1955 he was engaged mainly in the Weather Service Department and at the same time was pursuing postgraduate studies in Meteorology under Professor R. Fjørtoft. In 1955 he joined the staff of the International Meteorological Institute in Stockholm, Sweden, where he served under Professor C.G. Rossby and participated in the early operational aspects of the introduction of numerical weather prediction in the Swedish Weather Services. He completed his degree in Meteorology at the University of Stockholm in 1957 and his doctoral degree in 1960.

From 1959 to 1961 he was a staff member of the Joint Numerical Weather Prediction Unit, Suitland, Maryland, USA, where he continued his research on numerical weather prediction and the general circulation of the atmosphere. He joined the staff of the National Center for Atmospheric Research where he served as an Assistant Director in the Laboratory of Atmospheric Science from 1961 to 1963 when he was appointed as Professor and Chairman of a newly established Department of Meteorology and Oceanography at the University of Michigan, Ann Arbor, Michigan, USA. He served the University of Michigan until 1974 except for the academic years 1969–70 and 1971–72 when he was a Visiting Professor at the Universities of Copenhagen, Denmark, and Bergen, Norway, respectively.

The European Centre for Medium Range Weather Forecasts was created in 1973 by 17 European countries. Professor Wiin-Nielsen was engaged as Head of the Planning Staff in 1974 and became the first Director of the Centre when it was formally established in November 1975. He served in this position until he was appointed Secretary-General of the World Meteorological Organization.

Professor Wiin-Nielsen has been President of the International Commission on Dynamic Meteorology, a Member of the Joint Organizing Committee for the Global Atmospheric Research Programme, a Member of the Scientific Advisory Committee to the Director-General of the European Space Agency and Chairman of the Earth-oriented Space Research Group, and a Member of the Scientific Advisory Committee for the Max Planck Institute for Meteorology. He is also a Fellow of the American Meteorological Society, a foreign Member of the Royal Meteorological Society and of the Finnish Academy of the Sciences and the Arts, and a Member of the Norwegian Geophysical Society. Professor Wiin-Nielsen is the author of numerous scientific papers on subjects in atmospheric dynamics, numerical weather prediction and the general circulation of the atmosphere. He has also written a textbook on dynamic meteorology.

The Wihuri International Prize for 1983 amounts to US $30 000.

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NOTICES

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